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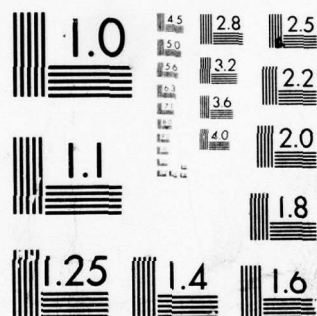
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TRANSDUCERS TO MEASURE VELOCITY, ANGLE OF ATTACK AND ANGLE OF SIDE SLIP
FOR THE ADVANCED SUBMARINE CONTROL PROGRAM

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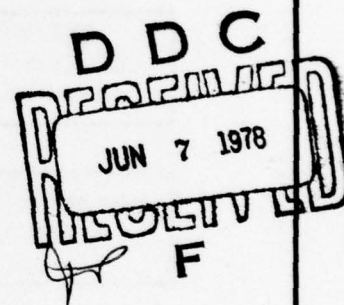
DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER



Bethesda, Md. 20084

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DAVID R. ARMSTRONG



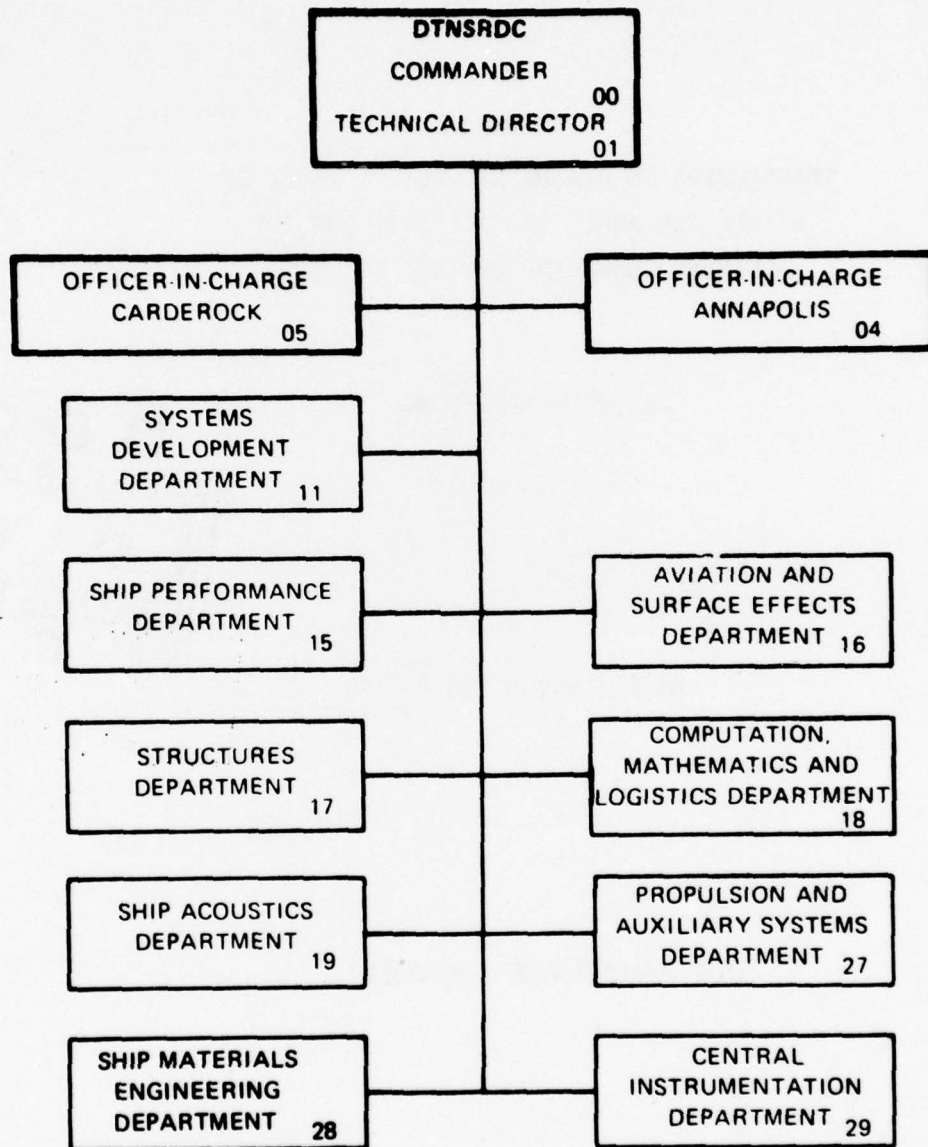
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ABSTRACT

A survey is presented of available transducers to measure relative velocity, angle of attack and angle of side slip for possible use on the ASCOP Free Running Model Submarine. After an examination of these transducers, the Signet Mk15 paddle-wheel velocity sensor and the Rosemount Model 858AJ angle of attack/side slip sensor are recommended for use on the ASCOP FRM.

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INTRODUCTION

The Advanced Submarine Control Program (ASCOP) is an effort undertaken by the Naval Sea Systems Command (NAVSEA) which includes development of a free running research submarine scale model. Test data from this model vehicle will aid in the assessment of the impact of variations in submarine design parameters on the stability and control and the maneuvering characteristics of selected submarine configurations.

Part of the development effort for the ASCOP free running model (FRM) is the selection of sensors that are capable of making the required hydrodynamic and inertial measurements with the accuracy needed for system identification and evaluation of maneuvering characteristics. It is the aim of this report to survey the available transducers for measuring relative forward velocity, angle of attack and angle of side slip or drift. After an examination of each transducer's advantages and disadvantages, recommendations will be made for the best type of transducer to measure each of these parameters.

The measurement of a submarine model's relative velocity, angle of attack and angle of side slip are normally not required in typical model tests conducted at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) or elsewhere for that matter. Normally the model under test is rigidly fixed to the Towing Carriage by some type of strut or other type of support. The model velocity then is simply measured from the Towing Carriage velocity measurement system. The carriage velocity is measured electronically with very good accuracy and, when up to speed, can be maintained with excellent consistency. Angle of attack and/or side slip are usually fixed by accurately positioning the model on the rigid towing strut at the desired angles.

Within the past few years, experiments conducted at DTNSRDC with FRM submarines have necessitated the incorporation of a velocity transducer on the FRM. However, up until the inception of ASCOP, angle of attack and angle of side slip were not measured even on the DTNSRDC FRM experiments.

The ASCOP requirements for system identification and maneuver response characterization make it necessary to include in the ASCOP model sensor set, transducers to measure angle of attack, angle of side slip and model forward relative velocity.

Before exploring the various transducers available for measuring relative velocity, angle of attack and angle of side slip in a marine environment, the measurands should be defined.

The relative velocity; U , is the linear velocity of the origin of the body axes, fixed in a moving body, measured relative to the fluid in which it is moving. The angle of attack, α , is the angle measured from the X -axis to the projection of the line of motion relative to the fluid, onto the X -positive portion of the XZ plane, positive in the positive sense of rotation about the Y -axis. The angle of side slip or drift, β , is the angle measured from the line of motion relative to the fluid to the X -positive portion of the XZ plane. β is positive in the positive sense of rotation about the Z -axis. The angle of attack and the angle of drift are sufficient to completely define the orientation of the body axes with respect to the direction of motion of the body relative to the fluid¹.

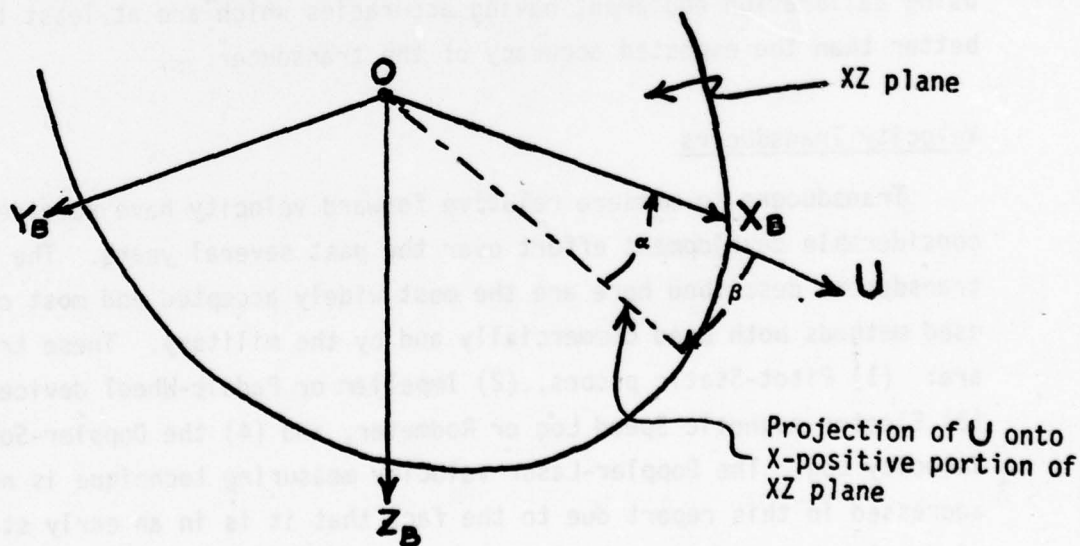


Figure 1 - Nomenclature for Angle of Attack and Angle of Side Slip

*A complete listing of references is given on page 25.

Several types of transducers for measuring ships' relative velocity have been developed by the marine industry which can be applied to measurements on model submersibles. However, transducers to measure angle of attack and/or side slip on submersible vehicles have not received the development in the marine industry as has been the case in the aerospace industry. As a result, most angle of attack of side slip transducers are modifications of aerospace transducers which allow for operation in marine environments.

Range and Accuracy Requirements

The operational speed range for the ASCOP FRM is 0.0 knots to 15.0 knots flank speed. The measurement of the FRM relative forward speed is to be accurate to within 0.1 knots over the entire operational range. The range of angle of attack and angle of drift encountered in submarine simulations performed at DTNSRDC are typically no greater than ± 15.0 degrees for each angle. ASCOP requirements call for transducers to measure these angles to within 0.3 degrees. It is important to note that the accuracy of any measurement is only as good as the calibration performed on the transducer making the measurement. Furthermore, it is important to calibrate the transducer on the actual test vehicle using calibration equipment having accuracies which are at least ten times better than the expected accuracy of the transducer.

Velocity Transducers

Transducers to measure relative forward velocity have received considerable development effort over the past several years. The velocity transducers described here are the most widely accepted and most commonly used methods both used commercially and by the military. These transducers are: (1) Pitot-Static probes, (2) Impeller or Paddle-Wheel devices, (3) Electro-magnetic Speed Log or Rodmeter, and (4) the Doppler-Sonar Velocity Log. The Doppler-Laser velocity measuring technique is not addressed in this report due to the fact that it is in an early stage of development and not yet practical for submersible model applications.

1. Pitot-Static Probe

The Pitot-Static Probe is probably the earliest developed method of measuring velocity in a fluid stream. While this transducer was used primarily as a device for measuring relative air-speed, it also has good applications as a device for measuring relative velocity of a body through water. There are some considerations that must be taken however, in applying the Pitot-Static probe to a water medium. First, the probe and piping to the pressure gage must be fitted with a device for bleeding out all trapped air to insure the pressure gage reads the true stagnation and hydro-static pressures. Second, the differential pressure gage must be capable of operating in a water medium at hydro-static pressures in the range of 125 psi with the required accuracy and resolution.

The calculation of velocity using the Pitot-Static probe is made by applying Bernolli's equation:

$$P_{stag} = \frac{1}{2} \rho V_B^2 + P_{static}$$

where,

P_{stag} is the stagnation pressure

P_{static} is the hydrostatic pressure

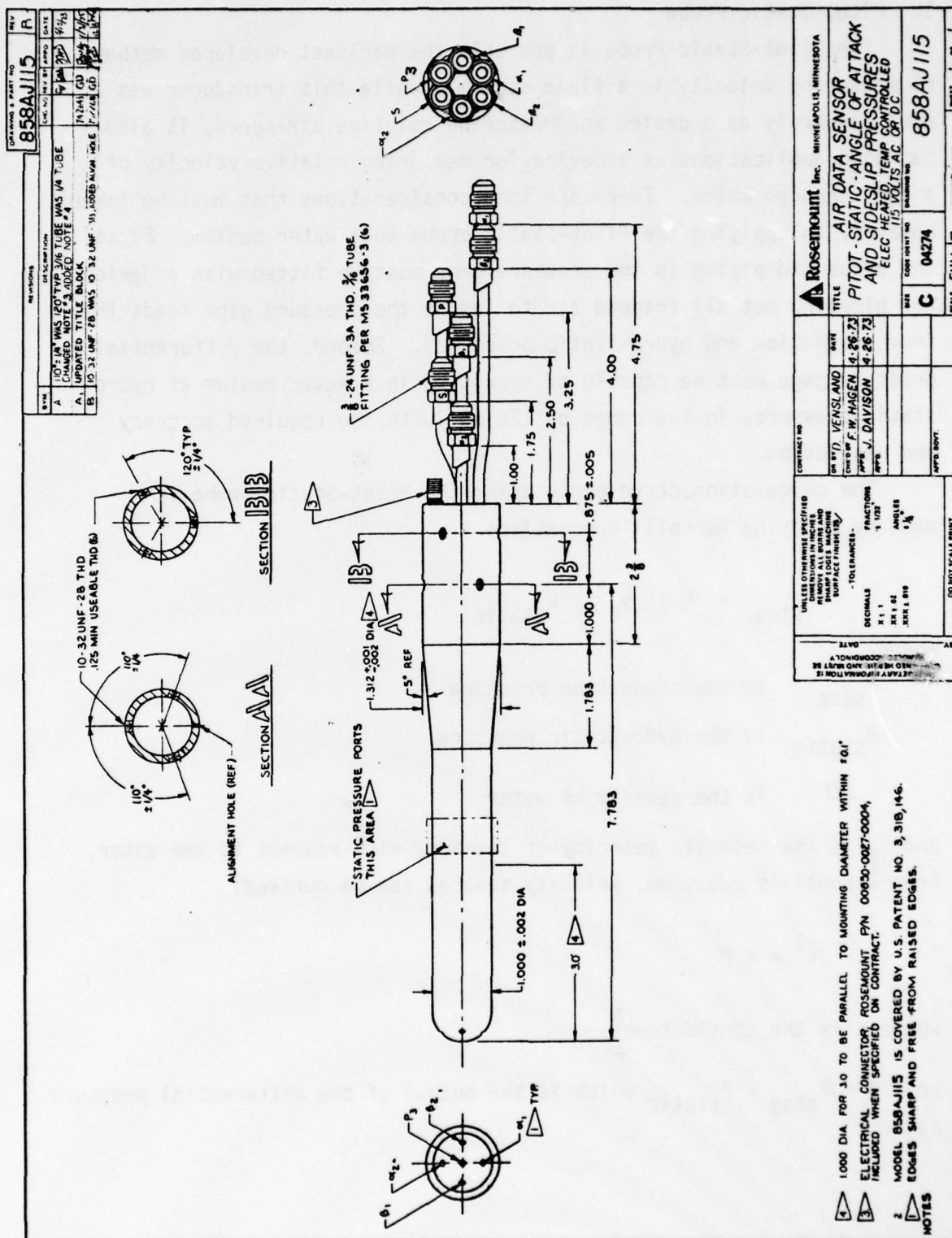
ρ is the density of water

and V_B is the relative velocity of the body with respect to the water. From Bernolli's equation, velocity squared can be derived:

$$V^2 = K P$$

where K is the constant $\frac{2}{\rho}$

and $P = P_{stag} - P_{static}$ which is the output of the differential pressure gage.



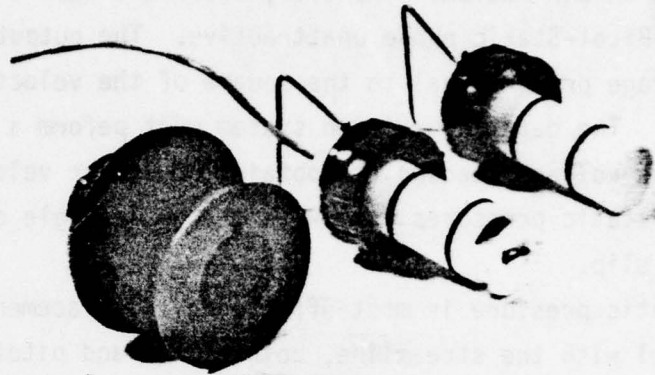
Notice that one advantage of using the Pitot-Static probe in water is that water, being an incompressible fluid, does not require that the pressure measurement be compensated for change of density and temperature as is required in air medium. However, there are several disadvantages that make the Pitot-Static probe unattractive. The output of the pressure gage is a voltage proportional to the square of the velocity and thus is non-linear. The data acquisition system must perform a square root function on the voltage reading to obtain the linear velocity. Furthermore, the pitot and static pressures vary with change in angle of attack and angle of side slip.

While static pressure is most affected by displacement of the probe out of parallel with the streamline, both static and pitot pressure will stay within 1 percent of full range over a displacement range of ± 5 degrees in both axes. Beyond this range the error increases substantially, but stays accurate to within 2 percent over a range of ± 15 degrees in both axes. Since the effects of angle of side slip and attack can be determined through calibration of the probe these errors can be compensated for as long as α and β are measured along with the speed.

A typical pitot static probe is the Rosemount, Inc. Model 858AJ (see Figure 2). This transducer is primarily a flow angle sensor, but also has provisions for measuring static pressure as well as pitot pressure. When used with a differential pressure transducer, such as the Rosemount, Inc., Model 1151DP, the Model 858AJ provides a velocity measurement which is better than 1 percent over a range of 0.0 knots to 15.0 knots at angles of attack and side slip of ± 5 degrees. The cost of the 858AJ is approximately \$1K and the cost of the 1151DP pressure gage approximately \$500.

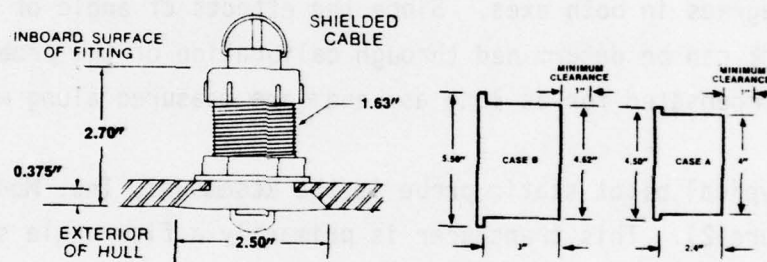
2. Paddle-Wheel Velocity Log

The paddle wheel type velocity log has been used at DTNSRDC on free running submarine model tests for a number of years with excellent results. The paddle wheel sensor generally consists of four paddles positioned at right angles to each other. Each paddle contains a small permanent magnet. When turned by the moving water, these paddles pass by an



MK 15

DIMENSIONS



MK15 Sensor



MK5 Knotmeter

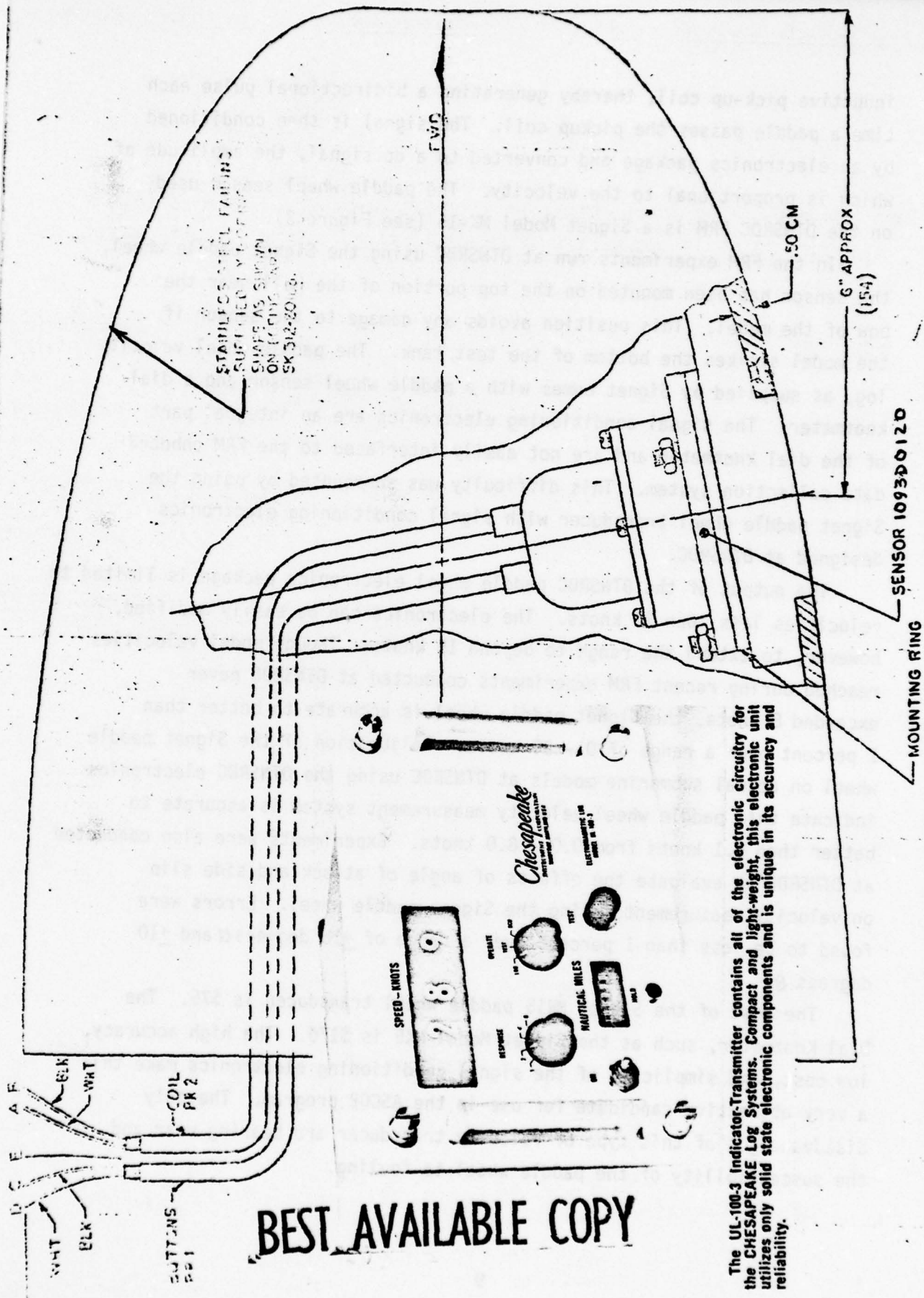
Figure 3 - Signet MK15 Paddle-Wheel Velocity Transducer

inductive pick-up coil, thereby generating a bidirectional pulse each time a paddle passes the pickup coil. The signal is then conditioned by an electronics package and converted to a dc signal, the amplitude of which is proportional to the velocity. The paddle wheel sensor used on the DTNSRDC FRM is a Signet Model MK-15 (see Figure 3).

In the FRM experiments run at DTNSRDC using the Signet paddle wheel, the sensor has been mounted on the top portion of the hull near the bow of the model. This position avoids any damage to the sensor if the model strikes the bottom of the test tank. The paddle wheel velocity log, as supplied by Signet comes with a paddle wheel sensor and a dial knotmeter. The signal conditioning electronics are an integral part of the dial knotmeter and are not easily interfaced to the FRM onboard data collection system. This difficulty was surmounted by using the Signet paddle wheel transducer with signal conditioning electronics designed at DTNSRDC.

The output of the DTNSRDC paddle wheel electronics package is limited to velocities less than 12 knots. The electronics can be easily modified, however, to extend the range to beyond 15 knots. Though model velocities reached during recent FRM experiments conducted at DTNSRDC never exceeded 8 knots, the Signet paddle wheel is accurate to better than 1 percent over a range of 0 - 30 knots. Calibration of the Signet paddle wheel on actual submarine models at DTNSRDC using the DTNSRDC electronics indicate this paddle wheel velocity measurement system is accurate to better than 0.1 knots from 0.0 - 8.0 knots. Experiments were also conducted at DTNSRDC to evaluate the effects of angle of attack and side slip on velocity measurements using the Signet paddle wheel. Errors were found to be less than 1 percent over a range of ± 18 degrees α and ± 10 degrees β .

The cost of the Signet MK15 paddle wheel transducer is \$75. The Dial Knotmeter, such as the Signet Model MK5 is \$170. The high accuracy, low cost, and simplicity of the signal conditioning electronics make this a very attractive candidate for use in the ASCOP program. The only disadvantages of this type of velocity transducer are bearing wear and the susceptibility of the paddle wheel to fouling.



The UL-100-3 Indicator-Transmitter contains all of the electronic circuitry for the CHESAPEAKE Log Systems. Compact and light-weight, this electronic unit utilizes only solid state electronic components and is unique in its accuracy and reliability.

Figure 4 - Gould/Chesapeake UL-100-3 EM Log Velocity Transducer

3. Electromagnetic Speed Log

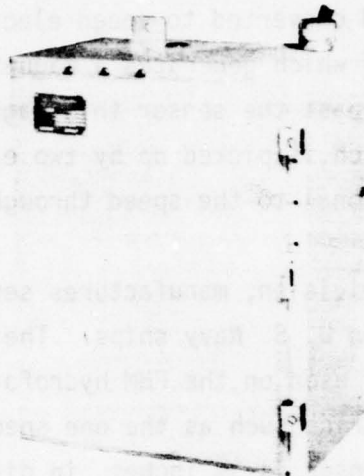
The electromagnetic speed log operates on an electromagnetic principle wherein a linear voltage proportional to speed is generated within an underwater sensor assembly and converted to speed electronically.

The sensor assembly contains a coil which generates a magnetic field in the water. As the water moves past the sensor this magnetic field induces a voltage in the water which is picked up by two electrodes. The voltage induced is linearly proportional to the speed through the water.

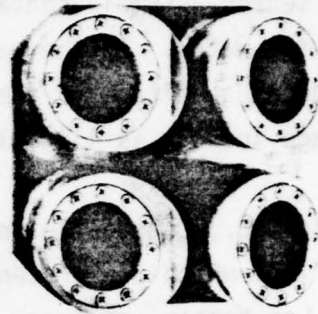
Gould Inc., Chesapeake Instrument Division, manufactures several EM speed logs which are presently used on U. S. Navy ships. The Gould EM Speed Log sensor, part no. 1093D0120, used on the PHM hydrofoil is small enough to be used on a model submarine such as the one specified for ASCOP (see Figure 4). The PHM EM sensor is $3\frac{1}{2}$ inches in diameter and is sealed to allow for operation in a flooded chamber. This sensor is flush mounted through a hull penetration. When the EM sensor is used with the Gould Model 100-3 electronics, it can provide a signal which has a resolution of 0.05 knots over a range of 0 to 20 knots and a total accuracy of better than 0.5 percent over the entire range. The output can either be a 12 bit binary output or a dc voltage scaled at 0.1 vdc/knot.

The EM velocity sensor is not susceptible to mechanical wear since there are no moving parts. It is also less susceptible to fouling than a paddle wheel type sensor. The chief disadvantage of the Gould UL-100-3 velocity measurement system is the size of the electronics package available from Gould (which includes velocity indicators and transmitters) which would make it impractical for model applications.

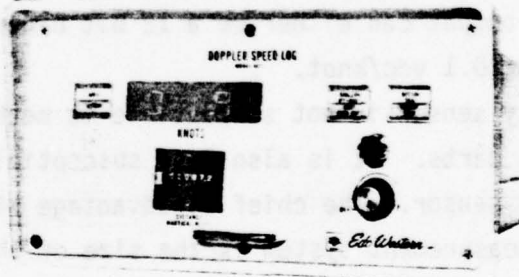
A specially designed electronics package would have to be designed and built. Another inherent disadvantage is the effect of boundary layer disturbances on the flow across the face of the sensor. The Navy Hydrofoil Program has experienced trouble with calibration of the EM log used on the PHM hydrofoil. The results obtained from actual measurements with the EM log do not fit the expected values obtained with the Gould calibration electronics. Furthermore, the EM sensor



Sonar Electronics Assembly



**Sensor Head
(Transducer Array)**



Main Display and Control

Figure 5 - Edo-Western Model 582C Doppler Velocity Transducer

itself is quite expensive, in the order of \$2,000. The UL-100-3 electronics package is approximately \$7,000. No estimate is available on the cost of developing and building the conditioning electronics to make this system adaptable to use in a model submarine.

4. Sonar-Doppler Velocity Log

The Sonar-Doppler velocity transducer is an electro-acoustic device which utilizes the Doppler frequency shift principle to generate a signal proportional to velocity. The Doppler principle states that the frequency of an observed signal differs from the frequency of the source whenever the source and the reference point are in motion relative to each other. Therefore, if the reference point and the source have a component of velocity parallel to the direction of the sound ray transmitted between the two, the number of waves-per-second shift from the original source frequency will be proportional to the relative velocity.

The Edo Western Model 582C is a good example of a commercially available Doppler velocity log (see Figure 5). This velocity log provides accurate over-the-ground velocity along ships axis. The transmit-and-receive transducer array is designed to be recessed flush with the vessel hull. The transducer array is watertight, allowing placement in flooded compartments. The system uses continuous wave and pulsed 455 kHz transmit/receive circuitry and operates from as close as six inches above and as far as 300 feet off of the ocean bottom. In water depths in excess of 300 feet, the system automatically switches to a pulsed mode of operation which obtains speed over the bottom as well as reliable speed measurements from the water mass without incurring turbulence error.

The transducer head contains two pair of transmit/receive transducers which provide dual acoustic beams in the fore and aft directions. Because the velocity, as measured by the forward looking beams, is compared with the velocity, as measured by the aft looking beams, the Model 582C cancels the effects of static inclination, pitch, roll, vertical motion, and boundary layer.

In the CW mode of operation, the system has a resolution of 0.01 knot at speeds up to 2.0 knots and 0.1 knot at speeds up to 30 knots. Total accuracy of the system is better than 1 percent of full range. In the pulsed mode, the total accuracy falls off up to 2 percent of full range.

Unlike the Pitot tubes, EM and paddle wheel velocity logs mentioned earlier, the Model 582C provides true over-the-ground speed in water depths to 300 feet. Furthermore, the output is available as a BCD word suitable for interfacing to a computer. A disadvantage of the system is its large size; the sensor head is nearly 3.5 inches in diameter and the electronics assembly is 15 inches by 20 inches by 9.5 inches. Furthermore, in order to get the desired output, the display electronics must also be used. This package is 13.5 inches by 7 inches by 10.15 inches. Powering the system also is a problem since it operates off of 115 VAC; however, the unit could be converted to run off of 28VDC. the system is also quite expensive; running nearly \$10,000 in its standard form.

Transducers to Measure Angle of Attack and Side Slip

The development of transducers to measure angle of attack and angle of side slip have not, unfortunately, received the attention in the marine industry as has been the case in the aerospace industry. This probably was due to the fact that naval vehicles were not, until recently, characterized as being high performance vehicles, as are jets and missiles, requiring the measurement of these angles. With the development of high speed hydrofoils, surface effects vehicles and high performance submarines, requiring the measurement of these angles, several aerospace-oriented angle of attack/side slip transducers were adapted for use in the marine environment.

Two such modified aerospace angle of attack/side slip transducers have been used by Boeing in their Hydrofoil Program and by Bell Aerospace Co. in their Surface Effects Vehicle program with some success. These

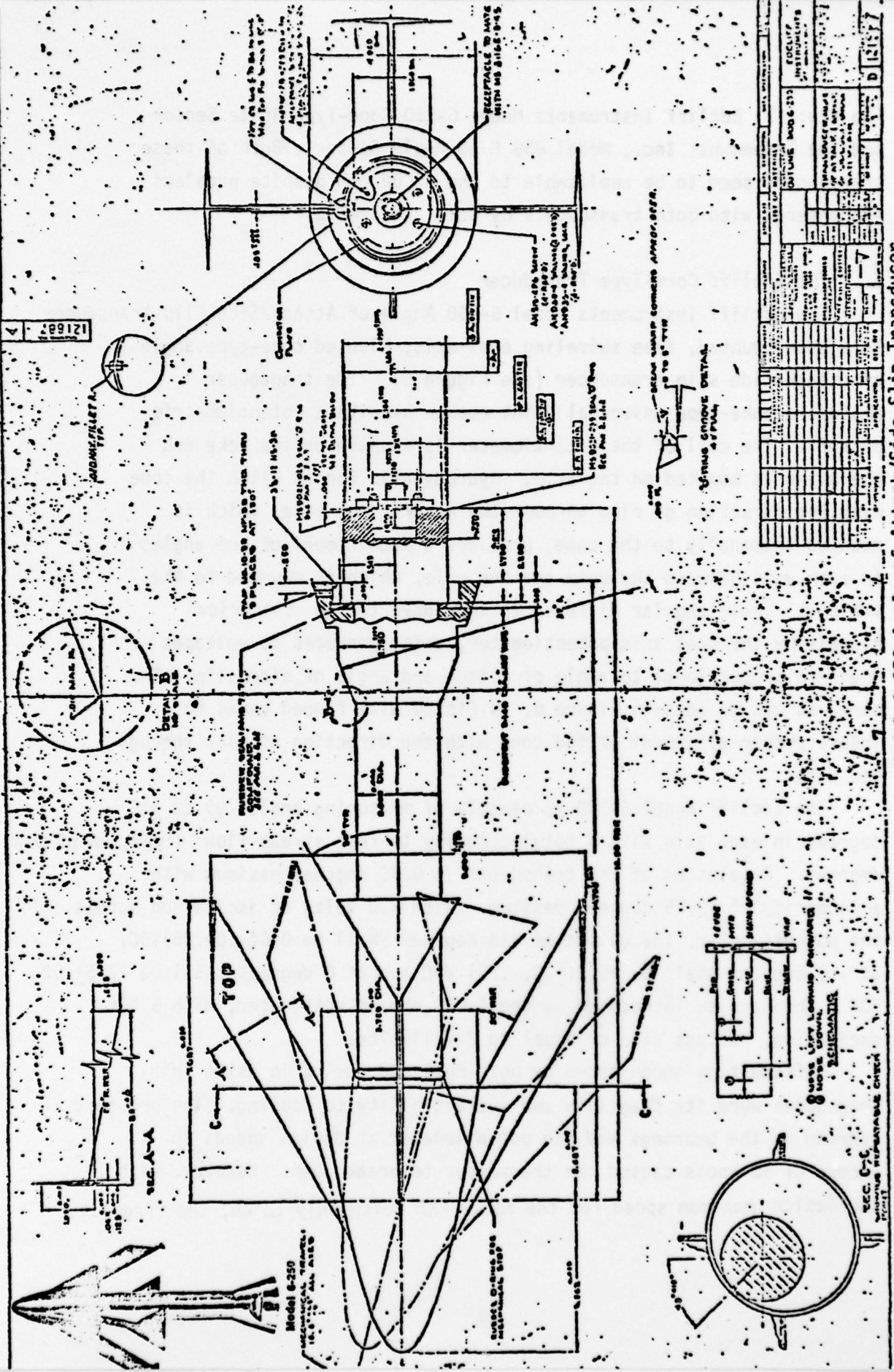


Figure 6 - Edcliff Instruments Model 6-250 Angle of Attack/Side Slip Transducer

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two are: (1) Edcliff Instruments Model 6-250 Cone-Type Angle Sensor and the Rosemount, Inc., Model 858 Flow Angle Sensor. Both of these transducers seem to be applicable to the ASCOP FRM despite problems encountered with both transducers by Bell and Boeing.

1. The Edcliff Cone-Type Transducer

The Edcliff Instruments Model 6-250 Angle of Attack/Side Slip transducer is a boom mounted, free swiveling dual-axis, blunted cone-type angle of attack/side slip transducer (see Figure 6). The transducer employs a yoke-type universal joint mechanism with a potentiometric pickoff. The coil of the potentiometer is mounted on the yoke and the wiper is mounted on the axle. Hydrodynamic forces align the cone with the direction of flow through the water. The yoke, which is mounted internally to the cone, provides a measurement of the angles in each axis between the cone and the axle, which is mounted to the vehicle. These angular differences are converted to electrical signals by the dual axis potentiometer, which produces dc voltages that are proportional to angle of attack and angle of side slip. The cone, as can be seen in Figure 6, is fitted with finned vanes to insure proper alignment of the cone with the direction of flow through the water.

The Edcliff Model 6-250 is capable of measuring angles up to ± 15 degrees in each axis with a total accuracy to free stream flow direction of 0.3 degrees. Resolution of the transducer is 0.05 degrees maximum with a linearity of ± 0.15 degrees maximum. With 5.0 volts dc excitation across the potentiometer, the output at $+15$ degrees shall be $0.0(-.0+.25)$ VDC, at -15 degrees shall be $+5.0(+.0,-.25)$ VDC and at 0 degrees shall be $+2.5 \pm .02$ VDC. Total noise introduced by the 4,000 ohm potentiometer, with 5 VDC excitation, is less than or equal to 2 millivolts.

Difficulties encountered by both Bell and Boeing in using this transducer were its fragility and susceptibility to fouling. The pressure exerted in the bearings and the potentiometer at design speeds in excess of 50 knots caused the transducer to break down. However, with the design maximum speed for the ASCOP FRM being only 12 kn, the fragility

encountered at higher speeds should be no problem. There is also a minimum hydrodynamic force against the cone that is required to overcome the inertia and friction of the bearings and the potentiometer. This means that there is a minimum velocity (not known) which must be reached before the cone will align itself with the direction of flow. Both Bell and Boeing were using the transducer in the open ocean, and found that the vanes on the cone made the device susceptible to fouling due to seaweed and other debris suspended in the ocean water. This could present a problem if the ASCOP FRM is operated in the open ocean. The ability of this transducer to maintain its waterproof integrity at the depths likely to be encountered by the FRM is not known. The output of the transducer being a dc voltage directly proportional to the angle of side slip and angle of attack makes the device attractive for use on model research vehicles. The Model 6-250 sensor is fairly expensive, costing \$4,200.

2. Rosemount Flow Angle Transducer

The inclination of a cylindrical probe with a hemispherical head to the surrounding flow can be sensed indirectly by calibrating the position of the probe against the pressure existing at ports drilled axially and laterally on the hemispherical head. Such a transducer can be used to measure the angle of attack and angle of side slip of a body moving through a fluid. To make these measurements the probe would have five holes drilled in the hemispherical head, one axially and four laterally. The four lateral ports are aligned on the axes of symmetry as shown in Figure 7. Such a device is known as a five-hole spherical Pitot tube. The two vertically positioned lateral ports P_1 , and P_2 , sense the pressure differential due to angle of attack. The two horizontally positioned ports, P_3 , and P_4 , sense the differential pressure due to angle of side slip. With the probe aligned with the direction of flow the pressures sensed at all lateral ports are equal. As the body, on which the probe is mounted, rotates to a positive angle of attack, the pressure port P_2 , becomes greater than the pressure

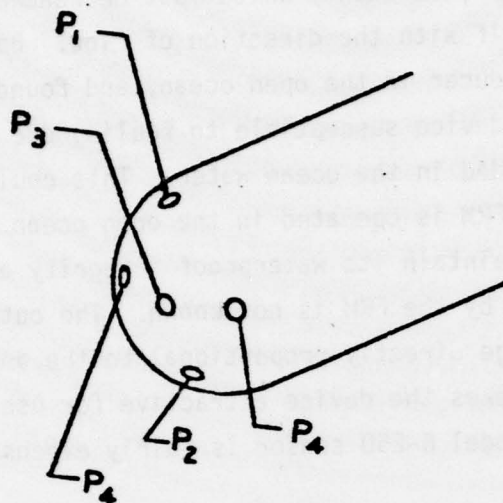
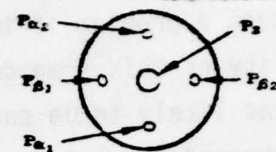


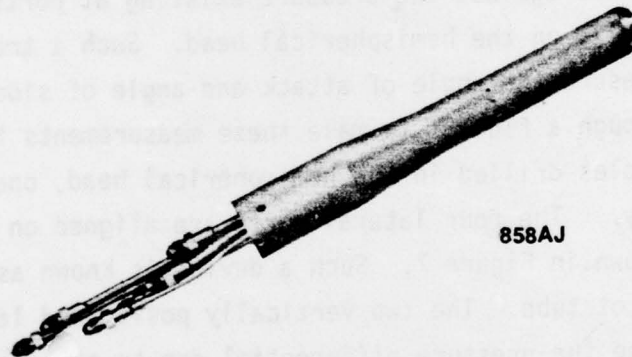
Figure 7



DIFFERENTIAL OUTPUTS

$$(P_{\alpha 1} - P_{\alpha 2}) (P_{\beta 1} - P_{\beta 2}) (P_3 - P_{\beta 1})$$

Figure 9 - Angle of Attack and Side Slip Configuration



858AJ

Figure 8 - Rosemount Model 858AJ Flow Angle Transducer

at the port P_2 . The greater the angle of the body in reference to the relative flow of the fluid, the greater the pressure differential between the two ports. The angle of attack can be computed as a function of $P_1 - P_2$, for either positive or negative angles. The same applies to ports P_3 and P_4 in computing angle of side slip. These pressures are transferred from the ports by internal pneumatic tubes to differential pressure transducers where the pressure differentials are converted to dc voltages proportional to the pressure differential.

The five-hole Pitot tube has been used at DTNSRDC for many years in measuring the direction and velocities of wakes behind ship models. However, little use was made of the five-hole Pitot tubes developed at DTNSRDC in measuring angle of attack or angle of side slip of ship models.

The theory behind the five-hole Pitot tube developed at DTNSRDC and the method of calibrating the probe are given in Reference 2.

The five-hole spherical Pitot tube has distinct disadvantages when compared to devices whose sensors are hydrodynamically driven into alignment with the local flow. The five-hole Pitot tube transducer cannot indicate directly the inclination of the local flow by its angular displacement relative to its mounting as the cone-type sensor can for example. The pressure signal output must be converted to an angle indication by a computer. However, this disadvantage is offset because this kind of sensor offers improved reliability in that it has no moving parts³.

The Rosemount Model 858AJ Flow Angle Sensor (Figure 8) is an excellent example of the commercially developed five-hole spherical Pitot tube. The Model 858AJ is a boom mounted device originally designed for use on aircraft. However, the sensor can be used in a marine environment provided differential pressure gages designed to operate in water are used.

Rosemount recommends the use of a special normalizing procedure in calculating the values of α and β with pressures sensed using their probe⁴.

This method eliminates the need for special calibrations to account for differences in local conditions between the sensor head and a remote point on the cylindrical body for g_{c1} and pitot pressure measurements. The local impact pressure at the sensing head, g_{c1} , is the difference between the local pitot pressure sensed at the axial positioned port, P_3 , and the local static pressure sensed at ports positioned on the cylindrical body of the probe. The differential pressure $P_1 - P_2$ is proportional to the product of g_{c1} times α_l ; where α_l equals the local angle of attack. However, if the two lateral ports in the horizontal plane are manifolded together, they will sense an approximate local static pressure. Then the difference between the center port, P_3 , and the approximate local static pressure can replace g_{c1} .

The Rosemount sensor, when configured as in Figure 9, provides both angle of attack and angle of side slip. In this case the horizontal lateral ports, $P_{\beta 1}$ and $P_{\beta 2}$, are not manifolded together, but individually sensed as are vertical lateral ports, $P_{\alpha 1}$ and $P_{\alpha 2}$. The manifolded pressure is replaced with a correction term which averages the side slip pressures $P_{\beta 1}$ and $P_{\beta 2}$. Three differential pressure measurements are then required; $(P_{\alpha 1} - P_{\alpha 2})$, $(P_3 - P_{\beta 1})$ and $(P_{\beta 1} - P_{\beta 2})$. The following equations can then be used to determine local angle of attack, α_l , and local angle of side slip, β_l :

$$\alpha_l = \frac{P_{\alpha 1} - P_{\alpha 2}}{K_1 \left[(P_3 - P_{\beta 1}) + \left(\frac{P_{\beta 1} - P_{\beta 2}}{2} \right) \right]}$$

$$\beta_l = \frac{P_{\beta 1} - P_{\beta 2}}{K_1 \left[(P_3 - P_{\beta 1}) + \left(\frac{P_{\beta 1} - P_{\beta 2}}{2} \right) \right]}$$

where K_1 is the sensitivity coefficient calculated by Rosemount for their probe. In the water media at the velocities reached by the ASCOP FRM, K_1 equals 0.088. K_1 is essentially constant for angles up to ± 40 degrees.

In this configuration, the Model 858AJ is manufactured to be accurate to ± 0.1 degrees over a range of ± 40 degrees. Total system accuracy is ± 0.25 degrees when used with a differential pressure gage such as the Rosemount Model 1151DP. This Model 1151DP capacitance-type differential pressure gage is designed for use in either fresh or salt water media. It can also withstand the range of hydrostatic pressures (up to 130 psi) and hydrodynamic pressures (up to 15 psi) likely to be encountered by the ASCOP FRM. Total accuracy of the Model 1151DP pressure gage is ± 0.2 percent of the calibrated span. This includes the combined effects of linearity (± 0.1 percent), hysteresis (0.05 percent) and repeatability (0.05 percent).

Cost of the Model 858AJ probe is approximately \$1,000. Each Model 1151DP pressure gage (three required) is approximately \$500. Rosemount also has the Model 842 Angle of Attack and Side Slip Pressure Transducer which may be used instead of the three separate transducers. It can be fitted with differential pressure transducers which will operate in fresh water. Cost of the Model 842 is approximately \$6,000.

The Bell Aerospace Co. investigated using the Model 858AJ to measure angle of side slip for their Surface Effects Vehicle program. Unfortunately, at the high speed anticipated for their SES, in excess of 80 knots, the probe tended to cavitate on the hemispherical head. The problem seemed to be that the lateral ports were positioned at too large an angle from the axial port. This will not be a problem on the ASCOP FRM due to the low operational speed range.

There is an important consideration in using the Rosemount sensor in a water media. The probe and pneumatic piping to the pressure gage diaphragm must be fitted with a device for bleeding out all trapped air to insure the pressure gage reads the true pressures at the ports. Furthermore, the probe must be precisely calibrated on the model to insure the probe is properly oriented, and to account for the difference in α and β due to the local flow conditions at the point of measurement and the true angles of the model hull.

Conclusions and Recommendations

The characteristics of all the velocity transducers considered in this report are summarized in Table 1. From this summary and the discussion given in this report the most promising velocity transducer for the ASCOP FRM is the paddle wheel type characterized by the Signet MK 15 sensor. From the results gained in FRM experiments conducted at DTNSRDC using this velocity transducer, the paddle wheel velocity sensor provides the best performance per dollar cost available. If this device is used in the ASCOP FRM, the design for the DTNSRDC electronics package which converts the sensor signal to a dc voltage, could be made available.

The characteristics of the transducer to measure angle of attack and angle of side slip that were considered in this report are summarized in Table 2. From this summary and the discussion presented in this report, the Rosemount Inc., Model 858AJ and associated Rosemount pressure transducers clearly represents the best system for making these measurements on the ASCOP FRM. The cost of the system is nominal and the performance excellent, far in excess of the ASCOP requirements.

Since both of these sensors generate dc signals proportional to the measurements, they both must be converted to digital formats. Care must be taken to select an analog-to-digital converter that retains the accuracy of the measurement obtainable by the transducer. Furthermore, as stated earlier in this report, the accuracy of any measurement is only as good as the calibration performed on the transducer making the measurement. It is important that calibration of the transducer be performed on the actual test vehicle. The equipment making the calibration must have at least ten times the accuracy expected of the transducer. The facilities and equipment at DTNSRDC fulfill this requirement and have been used for this purpose countless times. The towing tanks and water tunnels at DTNSRDC offer the controlled conditions necessary for accurate calibration of these transducers on the actual test vehicle.

TABLE 1
VELOCITY TRANSDUCERS

<u>Type</u>	<u>Model</u>	<u>Range</u>	<u>Accuracy</u>	
Pitot/Static Probe	Rosemount, Inc. Model 858AJ	0-15 Knots	$\pm 1\%(w/\alpha, \beta = \pm 5^0)$ $\pm 3\%(w/\alpha, \beta = \pm 15^0)$	No mo Simpl
Paddle Wheel	Signet, Inc. Model MK 15 (DTNSRDC Electronics)	0-30 Knots	$1\%(w/\alpha, \beta = 0$ @ 30 Knots) $1\%(w/\alpha = \pm 18^0$ $\beta = \pm 10^0$ @ 8 Knots)	Output to ve Unaff Simpl packa
EM Log	Gould/Chesapeake Model UL-100-3 w/1093D0120 sensor	0-20 Knots	0.5%	No mo Less Digit
Doppler Sonar	Edo Western Model 582C	0-30 Knots	1%(CW Mode at depths up to 300 feet)	High True Digit Unaff and

2

TABLE 1

VELOCITY TRANSDUCERS

<u>Accuracy</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Cost</u>
(w/ $\alpha, \beta = \pm 5^\circ$) (w/ $\alpha, \beta = \pm 15^\circ$)	No moving parts Simplicity	Output must be measured with pressure gage Output proportional to square of velocity Affected by α and β in excess of ± 5 degrees	\$1,500 (w/pressure gage)
(w/ $\alpha, \beta = 0$ @ 30 Knots) (w/ $\alpha = \pm 18^\circ$ $\beta = \pm 10^\circ$ @ 8 Knots)	Output directly proportional to velocity Unaffected by α and β Simplicity of electronics package	Requires custom built electronics Susceptible to fouling Bearing subject to wear	\$75 (sensor only) Cost of electronics package varies
5%	No moving parts Less susceptible to fouling Digital Output	Large electronics package Must be converted to operation on model Affected by boundary layer disturbances Calibration Difficulties Expensive	\$2,000(sensor) \$7,000(Electronics package)
(CW Mode at depths up to 300 feet)	High accuracy True velocity in CW mode Digital Output Unaffected by α and β and boundary layer effects	Large electronics package must be modified for use on a model Very expensive	\$10,000 (as is)

TABLE 2

ANGLE OF ATTACK/SIDE SLIP TRANSDUCERS

<u>Type</u>	<u>Model</u>	<u>Range</u>	<u>Accuracy</u>	<u>Adv</u>
Cone Type	Edcliff Model 6-250	$\pm 15^{\circ}$ ea. axis	Total: 0.3° Linearity: $\pm 0.15^{\circ}$ Resolution: 0.05° @ speeds up to 12 Knots	Potentiometer pickoff Output direct proportional
5-Hole Spherical Pitot Tube	Rosemount, Inc. Model 858AJ w/3 Model 1151DP pressure gages	$\pm 40^{\circ}$ ea. axis	Flow Angle Sensor: Total: 0.1%(Sensor Only) $\pm 0.25\%$ (Total System) <u>Pressure Gage:</u> Total: $\pm 0.2\%$ Hysteresis: 0.05% Linearity: $\pm 0.1\%$ Repeatability: 0.05%	No moving parts High Reliability MTBF, 10,000 High Accuracy Wide Range Low Susceptible fouling

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P TRANSDUCERS

<u>Accuracy</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Cost</u>
$\pm 0.3^\circ$ Accuracy: $\pm 0.15^\circ$ Resolution: 0.05° Works up to depths	Potentiometric pickoff Output directly proportional to α and β	Susceptible to fouling Waterproof integrity at deep depths unknown Fragility of mechanism could be a problem	\$4,200
<u>Single Sensor:</u> $\pm 0.1\%$ (Sensor Only) Total System)	No moving parts High Reliability, MTBF, 10,000 hrs.	Output indirectly proportional to α and β Require computer to calculate α and β	\$1,000 (Sensor) \$500 (ea. for pressure gage)
<u>Pressure Gage:</u> $\pm 0.2\%$	High Accuracy	Require heavy duty differential pressure gage to operate within ASCOP FRM range	or \$6,000 (optional pressure trans- ducer package)
Precision: 0.05% Accuracy: $\pm 0.1\%$ Reliability: 0.05%	Wide Range Low Susceptibility to fouling	Necessary to bleed all air out of system	

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